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Kristi K. Laug (PL); John David Holtzclaw (SPARTA)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Lancaster CA

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Phillips Laboratory
OL-AC PL/RKES
4 Draco Drive
Edwards AFB CA 93524-7190

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Before we can say yes or no to this multiple use of laser power, we have several questions that must be answered. To answer these questions, we performed some simple laser power beaming experiments on existing solar thermal propulsion hardware. We will compare these data with data we get from strictly solar powered experiments using the same hardware. This paper is focused on the results from the laser power beaming experiment.

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VOLUMETRIC ABSORBER AS SOLAR ENGINE UTILIZING LASER THERMAL POWER FOR ENERGY INPUT

Kristi K. Laug
OL-AC Phillips Laboratory/RKES
Edwards AFB CA 93524-7190

John David Holtzclaw
SPARTA
Lancaster CA 93535

ABSTRACT

Money is currently earmarked by Congress for laser augmented power for satellites. This means that satellites that are currently under-powered or have low PV efficiency, may be rejuvenated by dosing them with laser power beamed from earth. In addition, Solar Thermal Propulsion schemes may be able to use laser power as an energy source in place of the sun when the sun's energy cannot be collected or is insufficient. Such cases include eclipses, earth's shadow, or other occlusions.

Before we can say yes or no to this multiple use of laser power, we have several questions that must be answered. To answer these questions, we performed some simple laser power beaming experiments on existing solar thermal propulsion hardware. We will compare these data with data we get from strictly solar powered experiments using the same hardware. This paper is focused on the results from the laser power beaming experiments.

INTRODUCTION

Recently there has been much emphasis on multiple uses for each component or system. Multiple uses for a given component or system, reduces cost and risk, while increasing reliability, responsiveness, versatility, flexibility, and reproducibility. This fosters commercialization, and in turn, possible profits for privately owned industry.[1]

Multiple-use components reduce cost because it is cheaper per unit/system/component to manufacture many items of one design than just a few. The more units manufactured, the better the manufacturer understands the characteristics, thereby decreasing risk. Consequently, the greater the demand, the greater the chance to test under different conditions. This increases reliability. Responsiveness increases because there are more sources. The job-shop for making them is replaced by a manufacturer. Reproducibility increases because the jigs are set up for runs of several, not just for one. At the same time, molds that are slightly different but within the tolerances of the original, increase versatility and flexibility.[2]

In an effort to use the same component or system in more than one device, and also to find a way to use laser power for more than one

[1]Kristi Karen Laug and Michael Ray Holmes, Solar Bi-Modal Power and Propulsion: Mission Concept Requirements, 1995 Joint ASME/JSME/JSES International Solar Energy Conference Proceedings, Maui HI, 19-24 March 1995, Vol 2, 927.

[2] Ibid, p. 928.

component, the USAF is researching innovative advanced propulsion concepts using existing hardware. One such concept that may prove highly competitive and efficient is solar thermal propulsion. Some of the components that may lend themselves to multiple use and commercialization are the following. Carbon tubes may serve as heat exchanger for us, and as a high temperature spring for the Space Shuttle. Our thin film polyimide concentrator materials may lend themselves to tank bladders. Some high temperature carbon materials used in our absorber can also be on the SCRAMJET. See Figures 1 and 2. The system may be used for orbit maneuvering or transfer (lift, hold and move) missions. Laser thermal propulsion may also provide high thrust mode for survivable maneuvering.

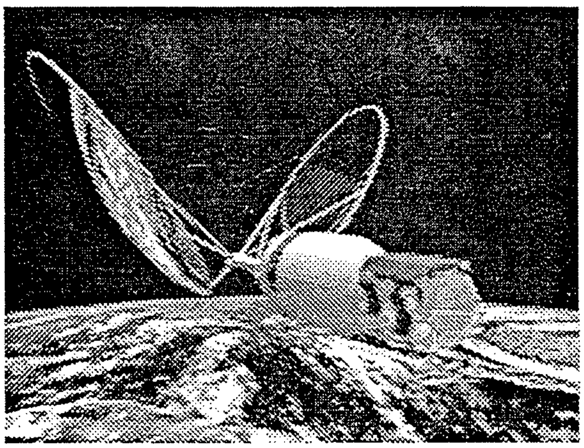

Fig. 1 Thermal Propulsion Rocket System

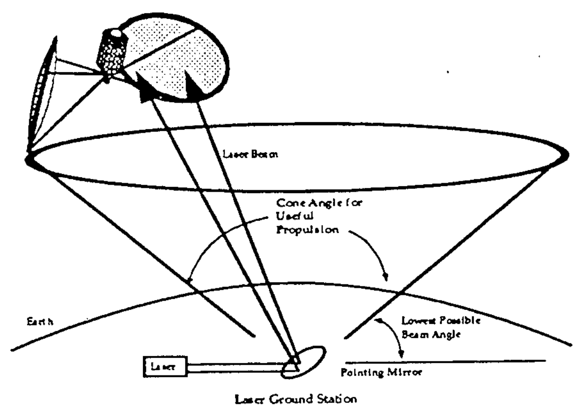

Fig. 2 Thermal Propulsion Operational Schematic

In this concept, solar energy is concentrated and used to energize a propellant thermally, then expand the heated propellant through a nozzle, producing thrust. One solar thermal propulsion issue that may be solved using laser energy as a power source, is occultation of sunlight caused by eclipse, shadow, or other inability to collect sunlight. This is also a multiple use of solar thermal propulsion components, namely concentrators and thrusters. In this scenario, laser energy is concentrated and used instead of solar energy to thermally energize a propellant.

OBJECTIVE

Operating Location (OL)-AC Phillips Laboratory (PL)/RKES was engaged in a project with PL/LIDB to prove the feasibility of using laser power beaming with solar thermal propulsion components. The goal of this project was to determine the feasibility of using our particular reticulated vitreous carbon calorimeter (RVCC) for use as a Laser Powered Rocket Engine (LPRE). LPRE is a propulsion device consisting of a structure with a cavity or surface where laser energy is focused and captured asthermal energy, which is then transferred to a working fluid such as helium or hydrogen. Figure 3 shows the differences between chemical propulsion and thermal propulsion. In thermal propulsion systems, the working fluid is heated by thermal energy and then expanded through a nozzle, producing thrust (kinetic

energy). Figure 4 depicts the differences between solar and laser thermal input on the same hardware.

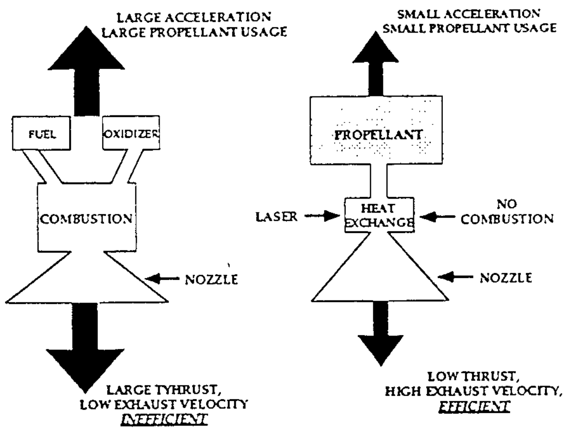

Fig.3. Operational Concept Comparison

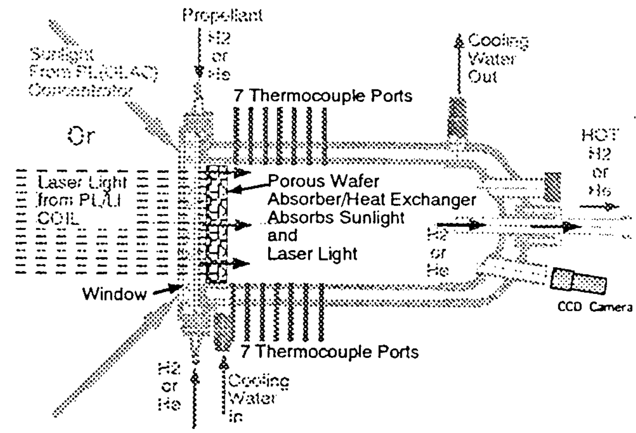

Fig.4 Solar/Laser Propulsion Concept

This particular OL-AC PL/RKES design is attractive for several reasons. It can be used with solar or laser thermal energy input. This design with laser power input will be tested in the solar furnace at Phillips Lab, Edwards AFB CA, then comparing the data with data accumulated during testing in the Chemical Oxygen Iodine Laser (COIL) facility at Kirtland AFB NM. With the laser power input, the engine should perform at high specific impulse and high thrust.

The goal of these tests is to generate data for thruster modeling. This engine will add important data to our repertoire of modeled engines at low cost to OL-AC PL/RKES. The final, long-term goal is to fabricate and fly the laser rocket engine in space.

The questions which must be answered in order to achieve these goals are: Can current propulsion schemes benefit from using laser power beaming as a supplement to defray the cost to one group, and instead spread the cost over many users? Can a solar thermal propulsion system use laser power as its primary energy source? Laser light can be focused much more intensely than sunlight, even after diverging over hundreds or thousands of kilometers. This means that the solar concentrators may be down-sized, saving weight and therefore cost. Producing much greater thrust from the same thruster with smaller concentrators is possible. This will allow faster trip times and cost savings for the customer. Can current facilities and personnel be used to experimentally validate the concept?

BACKGROUND

OL-AC PL/RKES participates in the research and development of a wide range of solar, laser, and bi-modal hybrid propulsion systems for use as upper stage orbital transfer vehicles. We are desirous of rendering those systems more capable through the introduction of advanced laser upper stage or orbital transfer vehicle propulsion concepts. We have conceptualized, designed and analyzed innovative approaches for laser powered rocket engines. We're in the process of

developing and fabricating one or more dual laser and solar-powered rocket engine prototypes.

PL/LIDB maintains the Air Force COIL Facility, a state of the art, laser-powered test facility with vacuum system capable of simulating altitude which is required to conduct controlled testing of laser usable hardware. They employ personnel experienced in setting up, troubleshooting, conducting and analyzing tests of lasers. They operate the COIL facility under various conditions to test a wide range of hardware. Equipment is kept in a high state of readiness, and personnel maintain a high degree of expertise. See Figure 5 for a top view of the COIL Laboratory. Also, see Figure 6, a view of the lab looking left and right from the lower right corner of Figure 5.

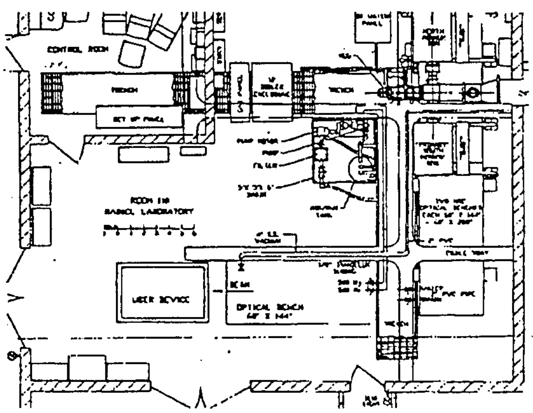

Fig. 5 COIL Laboratory Top View

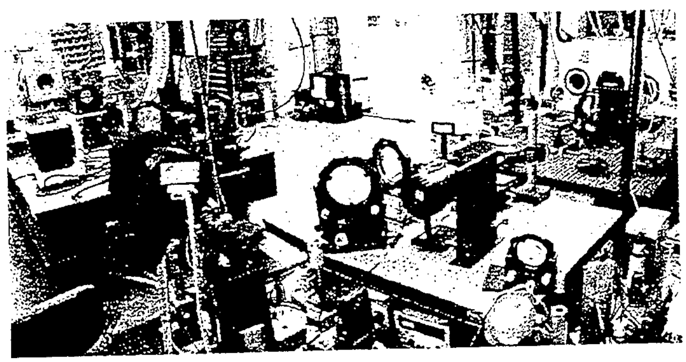

Fig. 6 COIL Laboratory

ADVANTAGES

The higher the temperature of the system (up to the thermodynamic limit of the light source (sun is 5800 K, laser is 10's of thousands K)), the higher the achievable specific impulse.[3] Also, laser light concentrates much more intensely than sunlight, increasing Isp.

High Specific Impulse may be achieved; possibly 1000 sec using hydrogen gas (cryogen) as the propellant or about 450 sec using ammonia (storable) as the propellant. Almost any gas can be used as the propellant: hydrogen, ammonia, hydrazine, helium, argon, etc. Only the propellant is carried to orbit. The laser energy source stays on Earth.

Thrust is proportional to the collected laser or solar power. If designed properly, the system could work satisfactorily in either laser or solar thermal propulsion mode. The entrance apertures of the absorber can be much smaller if operated in laser thermal mode only, because laser light can be focused to a much smaller point for the same input power. The solar mode would produce lower thrust

[3]Michael Ray Holmes and Kristi Karen Laug, Dependence of Solar-Thermal Rocket Performance on Concentrator Performance, 1995 ASME/JSME/JSES International Solar Energy Conference Proceedings, Maui HI, 19-24 March 1995, Vol 2, pp. 837-848.

during intervals when a laser ground station was not in view. During eclipse, the laser would allow continued thrusting.

We can test the solar mode of operation on the ground using existing solar thermal propulsion facilities and hardware. We can test the laser mode of operation on the ground using existing laser facilities and hardware. Short range tests of a few meters are all that are required. The existing PL/LIDB 10-20 kW (maximum power) laser facility (Chemical Oxygen Iodine Laser-COIL) can be coupled directly with the OL-AC PL/RKES's RVCC to determine achievable propellant temperatures. A concentrator could be added to focus light in the RVCC for a longer range test in the future. Beam divergence, deflection, and attenuation over a few thousand meters would simulate space conditions.

There are some unknowns that need to be resolved before longer range tests can be attempted. For instance, is continuous power available now or will it be available soon in the 10-20 kW power range? To design the concentrators we need tKnow the beam divergence and laser beam width. We need to perform mission analyses to direct the technology development.

Solar thermal propulsion can perform the LEO to GEO mission in a minimum of 10 days. With a laser thermal propulsion system, the trip time should be at least as short if not shorter because of the higher potential thrust.

DISADVANTAGES

Laser thrust is available only when the spacecraft is sufficiently above the laser's horizon for the beam to propagate reliably. Multiple laser sites will be required for some missions. The upper limit in effective exhaust velocity is determined by material limitations. The upper limit in thrust-to-weight ratio is determined by total power delivered to the thruster. Concentrators will be as large as or larger than the beam spot size only close to LEO. This spot size grows with increasing distance from Earth. Laser pointing must be very precise, and adjusted for atmospheric refraction.

Operation is limited by how low a laser beam can be pointed before atmospheric extinction reduces the transmitted power excessively. In LEO the spacecraft will be in range of the ground station only for a couple of minutes. (Laser beam power is one over distance squared from the ground station or $1/r^2$). The beam concentrating optics will be sized to get the required power at the most extreme operating distance. At GEO, the intensity could be low, but still possibly greater than one sun. Adaptive optics (required to get minimal divergence) directs much laser energy.

DESCRIPTION OF CONCEPT

A laser thermal propulsion system would probably consist of one or more ground based lasers trained on the concentrators of a regular solar thermal propulsion system. The solar thermal propulsion system consists of two primary concentrators, one or two thruster(s), propellant tank, controls, sun-tracking system, and other associated hardware. Sunlight or laser light is collected and focused through

two thruster apertures from the primary concentrators. The energy may be further focused by secondary concentrators. The thermal energy is then absorbed by the propellant via a heat exchanger. The propellant expands through the propulsive nozzle(s), thereby producing thrust. There is no ignition or combustion of the hydrogen propellant and no oxidizer is used.[4]

Concentrators have two degrees of freedom of movement to allow for power reception and thrust simultaneously.[5] Two concentrators are required to put the center of mass on the thrust line so that the spacecraft could be operated in a solar thermal propulsion mode.[6] Only one of the two mirrors needs to be used in laser mode. There are other configuration variations that may be considered. The size may be determined by mission requirements for thrust and available laser intensity.

EXPERIMENTS

LASER HARDWARE DESCRIPTION

Excited oxygen (O_2) is produced by reacting chlorine gas (Cl_2) with hydrogen peroxide in the O_2 generator. Then, in the I_2 generator, iodine atoms in the ground state ($5I_2P^{1/2}$) are stimulated to the magnetic dipole state as defined in Equation 1 below.

$$5I_2P^{1/2}=5I_2P^{3/2} \quad (1)$$

Finally, the metastable excited oxygen molecules are collided with the iodine molecules, producing the oxygen-iodine laser chemical reaction in the Chemical Oxygen-Iodine Laser (COIL).[7] The COIL beam is nominally rectangular in shape, approximately 165.1 mm (6.5 in) on a side. The COIL was focused in through a rectangular aperture of the PL RVCC cavity.

TEST HARDWARE AND SETUP DESCRIPTION

The RVCC cavity is 190.5 mm (7.5 in.) nominal internal diameter. It is approximately 457.2 mm (18 in.) in length. It converges down to 25.4 mm (1 in.) diameter at the throat. The RVCC is made of a 203.2 mm (8 in.) stainless steel pipe and one end cap nested inside a 254 mm (10 in.) stainless steel pipe and one end cap. At the other end is a 203.2 mm (8 in.) to 254 mm (10 in.) annular pipe cap, joining the two pipes. The seams are all welded. Long fins were welded in a helix around the outside of the inner pipe, to direct cooling water flow. See Figure 7. Reticulated vitreous carbon and/or hafnium carbide discs are pushed in through the front behind the window (which is removable) a specified distance. See Figure 8.

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[4]Kristi Karen Laug, Solar Propulsion Concept is Alive and Well at the Air Force Astronautics Laboratory, 1989 Joint Army Navy NASA Air Force Propulsion Conference Proceedings, Cleveland OH, CPIA Publication Pub. 515, Vol 1, pp.289-324.
[5]Ibid.
[6]Holmes, Dependence of Solar Rocket Performance on Concentrator Performance, pp. 837-848.
[7]K.A. Truesdell, S.E. Laberson, G.D. Hager, Phillips Laboratory COIL Technology Overview, 23rd AIAA Lasmadynamics & Lasers Conference Proceedings AIAA 92-3003, 6-8 July 1992.

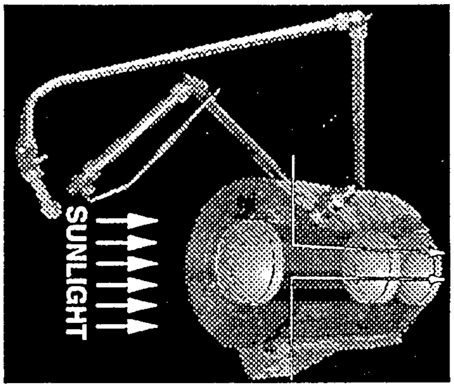

Fig. 7 RVCC Assembly Schematic

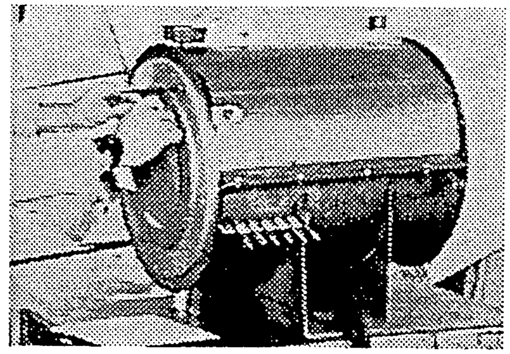

Fig. 8 RVCC Disc Installation

Helium propellant enters the front of the cavity (annular cross section) through a tube. It is held inside the cavity behind the quartz window. The helium propellant exited the opposite end, through a tube to a heat exchanger through which flowed a silicon/water mixture (1325 ml silatherm in 120 sec) at approximately -30 ^{O}C (-22 ^{O}F).

There are 14 sealed thermocouple ports inserted through the double walls of the RVCC, 2 each station, 180 degrees apart, axially. There are 12 Type C (26% tungsten/5% rhenium) thermocouples inserted into the instrumentation ports along with one pressure transducer. Seven "stations" were designated. The stations served as positioning locations for the wafers. Two types of wafers were inserted: carbon (C), and hafnium carbide chemical vapor deposited (CVD) on carbon blanks (HfC). The wafer porosity ranged from 10 to 100 ppi. The test matrix pitted the wafer porosity against type against power rating as a minimum. We used a statistical design of experiments method to determine our test matrix. It was loosely based on Taguchi's Design of Experiments.[8] Our design mapped out many more parameters and variables than was practical, using Taguchi's methods. See the paragraphs below for more information.

The 12 Type C thermocouples, three pressure transducers, and one resistance temperature device (RTD) were augmented by a Dynamics 7200 signal amplifier. Then the data was sent to a 486 chip computer which ran the data acquisition software which was written in-house by PL/LIDB personnel.

The following Figures 9, 10, 11, and 12, are of the evacuated/baked/lased wafers. In order to deal with the rectangular laser beam, we had to insert an aperture in front of the wafers.

[8]Tom Zlebek, ITT Statistical Programs Group Presentation of Taguchi Methods, 19-26 Feb 1991, based on Dr. Genuchi Taguchi's Design of Experiments.

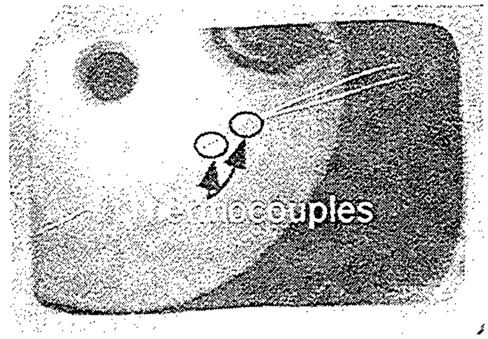

Fig. 9 Aperture Plate Only With Type C Thermocouples Protruding

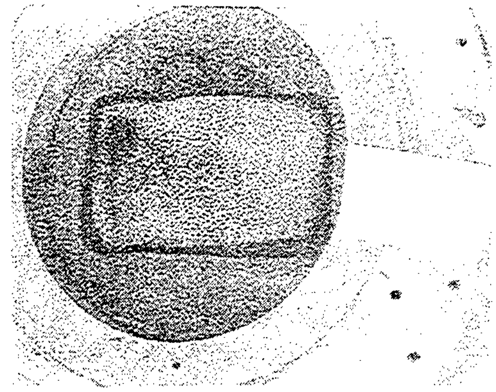

Fig. 10 Wafer Inserted Behind Aperture Plate After Lasing

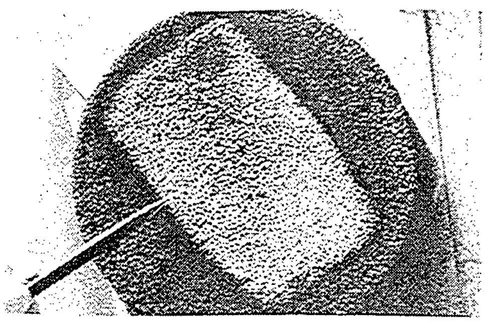

Fig. 11 Same Wafer as Fig. 10 After removal from RVCC

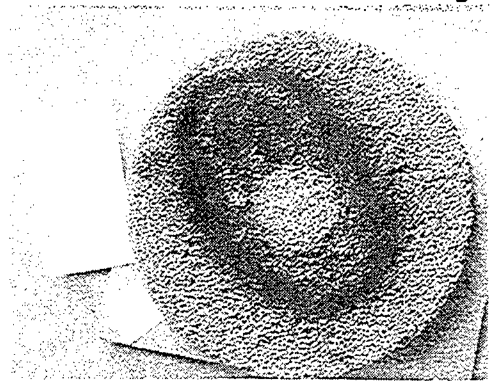

Fig. 12 Same Wafer as Fig. 11 Reverse

ASSUMPTIONS

During the summers of 1994 through 1995, the Solar Propulsion Group at PL/RKES worked on designing, fabricating, and testing the Reticulated Vitreous Carbon Calorimeter (RVCC) as a solar and laser test bed. First, we tested the HfC and C discs for porosity, coating density, coating deposition, water content, cracks, and appearance. We eventually had to assume the wafers would withstand the rigors of testing in laser or solar thermal input power. We baked and evacuated the wafers prior to testing.[9]

METHOD

DESIGN OF EXPERIMENTS

The Taguchi Design of Experiments method was chosen as a basis for determining the test matrix, and the individual tests that would be performed.

TEST MATRIX

[9]Kristi Karen Laug and Alan J. Baxter, Evaluation of Hafnium-Carbide Wafers for use in a Solar Calorimeter, 13th Symposium on Space Nuclear Power and Propulsion (SNPS), Proceedings of the Space Technology and Applications International Forum (STAIF-96), 8-11 January 1996.

Table 1. As Completed Laser Power Beaming Test Matrix

Solar Test#	Laser Test #	Batch	Power (kW)	Time (sec)	Energy (MJ)	Remarks
2	1	1	10	120	1	
24	2		8	480	4	
17	4	2	8	240	2	
39	5		6	480	3	
16	6	3	8	240	2	
33	7		6	480	3	
30	8	4	6	480	3	
4	3		10	120	1	
40	12	5	20	60	1	not completed
8	10		10	120	1	
31	11	6	6	480	3	
10	9		8	240	2	

SHORTCOMINGS

The test matrix is imperfect. Since it was based on Taguchi's Design of Experiments, there were supposed to be a specific number of parameters that were grouped, considered, and varied as part of the experimental design process. The idea was to shorten the number of tests, while increasing the knowledge about each test, and its relationship to other tests. This is supposed to cover several items of information per test that will correlate to other sets of data from the other tests. If the number of parameters grows to cover all of the possibilites, the matrix size gets unwieldy. It becomes impossible to determine the ANOVA table.[10] If the number is lessened, the matrix becomes suspect. This is what happened to ours. There were so many variables, and so many considerations, the parameters list which directly affects the output became very large (signal factors and noise factors), and seemingly impossible to correlate to get a realistic orthogonal array.[11] Therefore, we had to combine some, making the results less than optimum. See Figure 13 for sample test outlines.

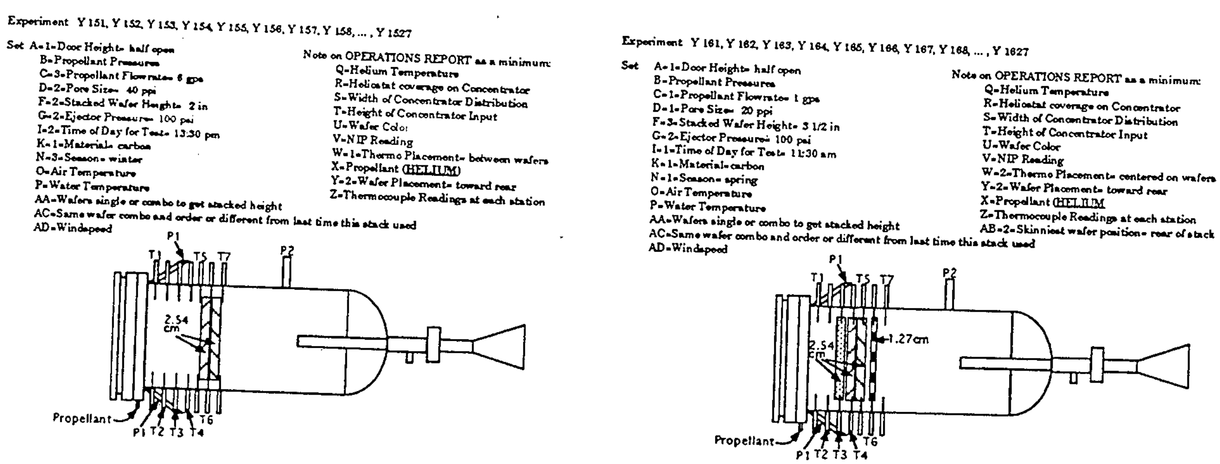

Fig. 13 Two Experimental Placements of Wafers for Specific Tests

[10]Tom Zlebek, Vol I.
[11]Ibid.

This test matrix was shortened from the much larger solar test matrix. We originally thought we could perform approximately 30 different experiments for a total of about 64 MJ. However, only 12 experiments were completed for a total of 26 MJ, or less than half. There were several reasons for this. One, the COIL peak power was less than expected for the test time duration. Also, their pump did not work as well as expected, and they had some pressure surging, causing problems with their optics (7.2 +/- 0.1% loss through). They couldn't pump enough BHP through to maintain power tKeep the BHP cool.

OPERATIONS

We inserted each wafer, or group of wafers depending on the test matrix, into the RVCC cavity. Then we tested them in the PL/LIDB COIL at power ranging from 1 kW to 12 kW, from 8 min. to 2 min., respectively.

DATA

We got good data from 4 shakedown tests and 12 actual tests. The following pictures are representative of all the tests. Fig. 14 shows the total absorbed average power absorbed into the wafers. Fig. 15 shows the total re-radiated power on average. The reradiation loss is about 30%.

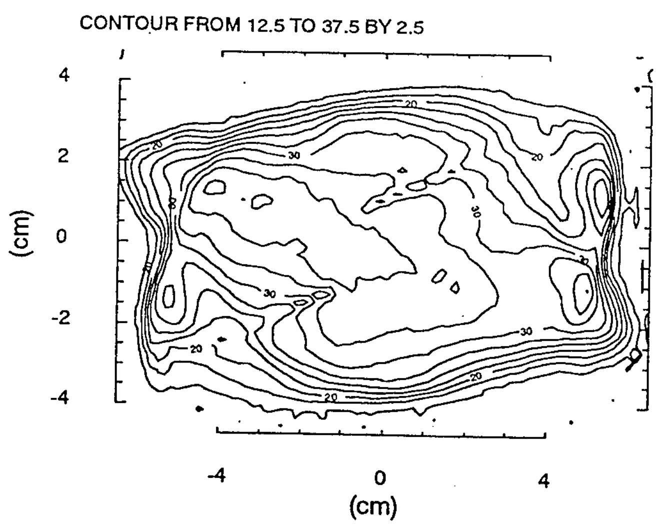

Fig.14 Re-Radiated Power

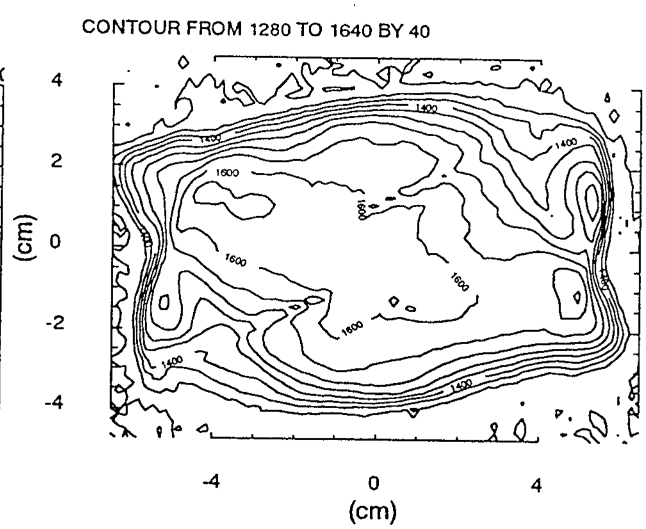

Fig. 15 Temperature

RESULTS/CONCLUSIONS

The reradiation that occurred can be lessened by adding a secondary non imaging concentrator in front of the heat exchanger aperture. This will allow us to reduce the diameter of the heat exchanger aperture to reduce reradiation. At the same time the primary

concentrator will have a larger target for which to aim: the larger entrance aperture of the secondary concentrator.[12]

At this point, let us revisit the questions posed at the beginning of this paper. Can current propulsion schemes benefit from using laser power beaming as a supplement to defray the cost to one group, and instead spread the cost over many users? Laser power beaming did not destroy the wafers, although they were damaged. The laser did heat the wafers, which in turn imparted thermal energy to the working fluid. It is too early to say whether the cost will be lessened. There aren't enough users at this time to make that determination. Can a solar thermal propulsion system use laser power beaming for its primary energy source? It appears this possible. We have been invited back when PL/LIDB upgrades their facility to higher power and increased test duration. We need more information. Can current facilities and personnel be used to experimentally validate the concept? Yes. Next test battery we will finish the test matrix.

SUMMARY

This experiment affords a good opportunity for OL-AC PL/RKES to demonstrate a new thermal rocket engine design for potential customers. At this time, most of the data is unreduced. When the data is reduced, it will provide the basis for a detailed engineering assessment of a second generation thruster based upon anticipated commercial user needs. This assessment will increase understanding of OL-AC PL/RKES's design approach in applying available materials for 'in-depth' laser energy coupling. Finally, this will permit us to gain engineering insight into commercial user needs and synergism with potential users.

OL-AC PL/RKES hopes to determine the feasibility of this engine for our own purposes. Later, after our RVCC is tested with sunlight, the database will be updated with the best RVC thruster design for our specific requirements.[13] We want increased Isp, increased efficiency, increased thrust, and increased chamber temperature above what our rhenium tube cavity thruster was able to attain. Eventually, one of these engines will undergo exhaustive reliability and maintainability testing at flight conditions in preparation for a space flight test mission from Low Earth Orbit (LEO) to Geosynchronous Equatorial Orbit (GEO).

[12]William R. Clayton, Paul Armin Gierow, and Luther T. Spears, Sub-Scale Testing of a Solar Rocket, 1995 ASME/JSME/JSES International Solar Energy Conference Proceedings, Maui HI, 19-24 March 1995, Vol 2, pp. 849-853.

[13]Kristi Karen Laug, Solar/Laser Thermal Propulsion Emphasizing Solar, ASME/JSME/JSES International Solar Energy Conference Proceedings, San Antonio TX, 31 Mar - 3 Apr 1996.